Measuring the Stellar and Planetary Parameters of the 51 Eridani System

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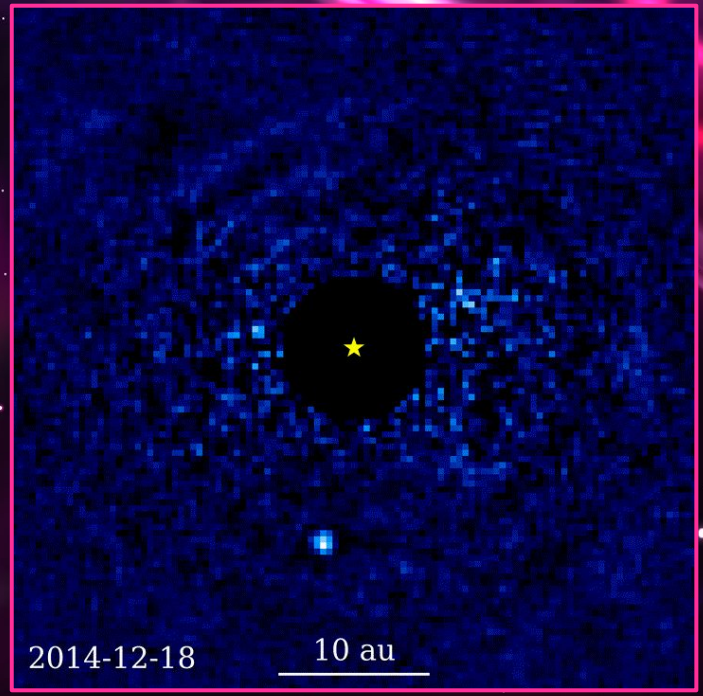
CHARA Science Meeting 2024



Jason Wang (Caltech)/Gemini Planet Imager Exoplanet Survey

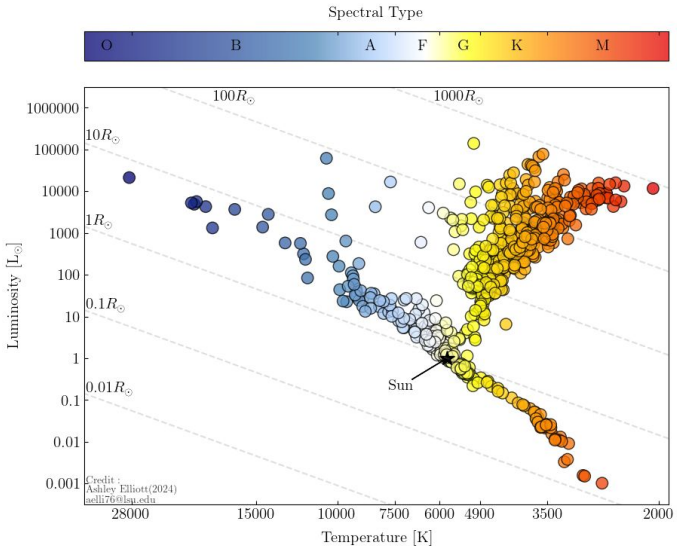
“Know thy star, know thy planet.”

★ **Direct measurements**
- Angular diameter
- Parallax
- Bolometric flux

★ **Derived stellar properties**
- Effective Temperature
- Luminosity

★ **Modeled properties**
- Age
- Mass

★ **Exoplanet characterization**
- Mass
- Insight on how planet was formed



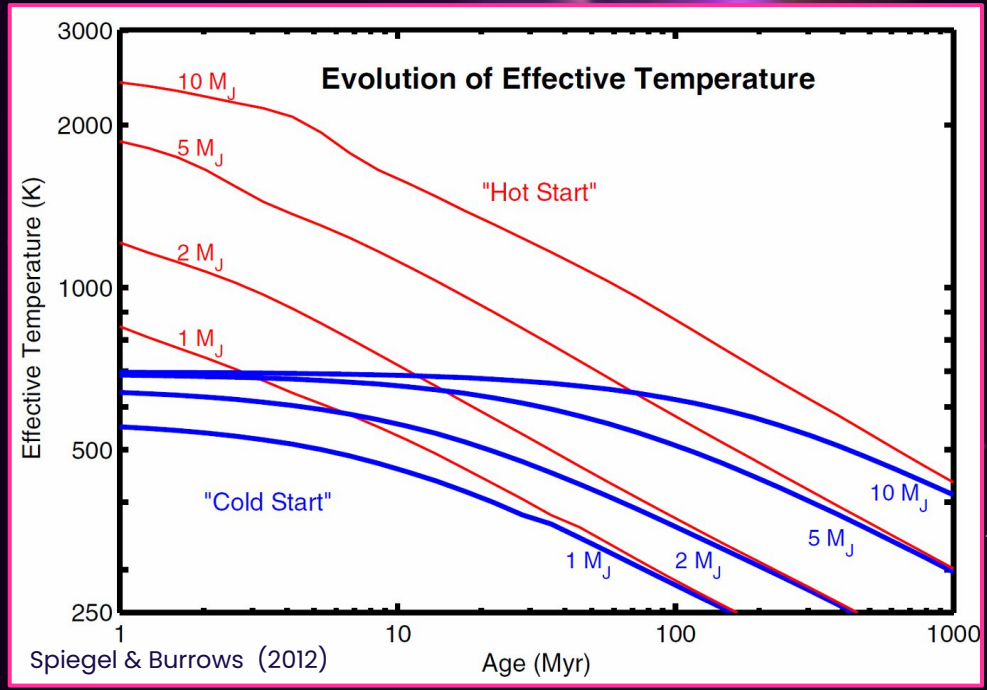
How do planets form?

"Warm" Start Model

- Spectrum of initial conditions instead of discrete processes
- Created to address the discrepancies between observations and theory predictions

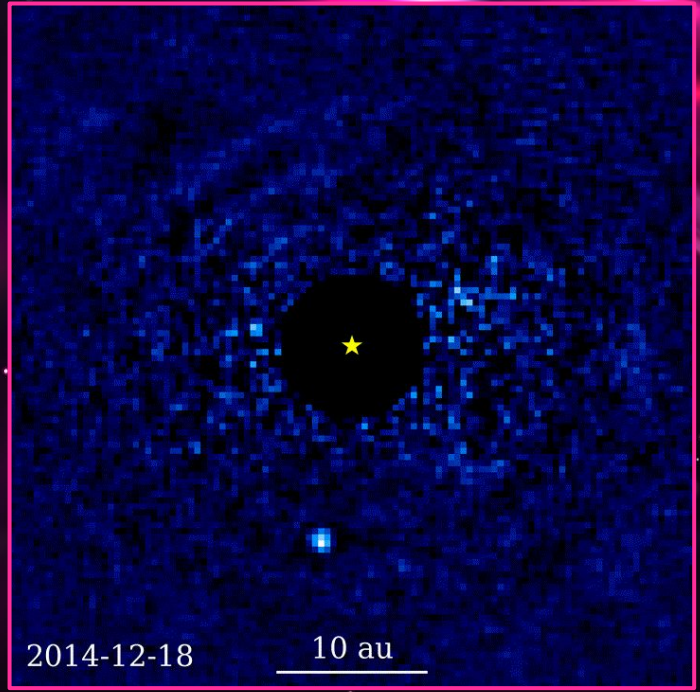
"Cold" Start Model

- Core accretion
  - Rocky core forms and material accretes onto the core
- Results in lower entropy and smaller radii



The 51 Eridani System

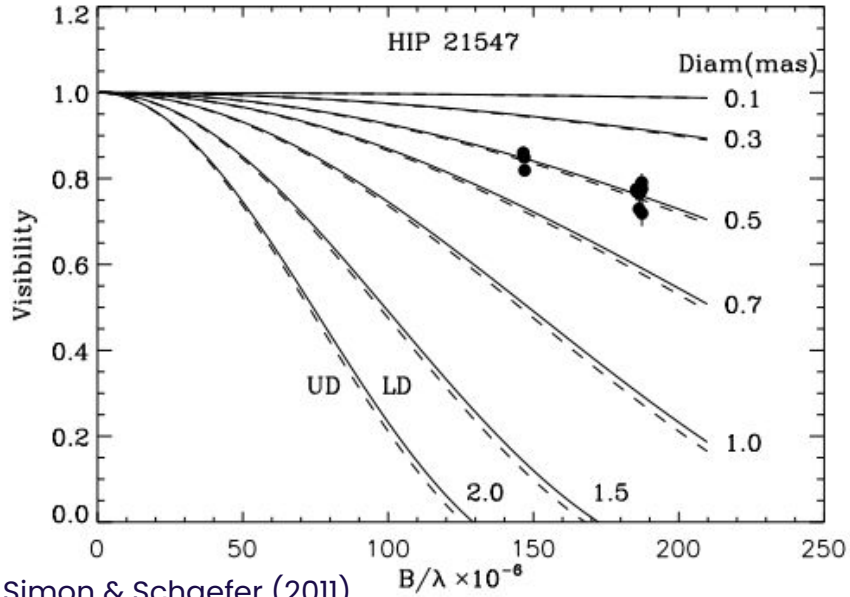
- ★ Composed of:
  - 51 Eridani
  - Binary system GJ 3305 AB
  - 51 Eridani b
- ★ 51 Eridani and GJ 3305 AB are separated by 66″
- ★ Planet was discovered in 2015 by Macintosh et al. via the Gemini Planet Imager (First one!!)
- ★ A member of the β Pictoris Moving Group
  - Young, nearby group of stars
  - Ages: ~10–30 Myr



Jason Wang (Caltech)/Gemini Planet Imager Exoplanet Survey

Past Work on the 51 Eridani System

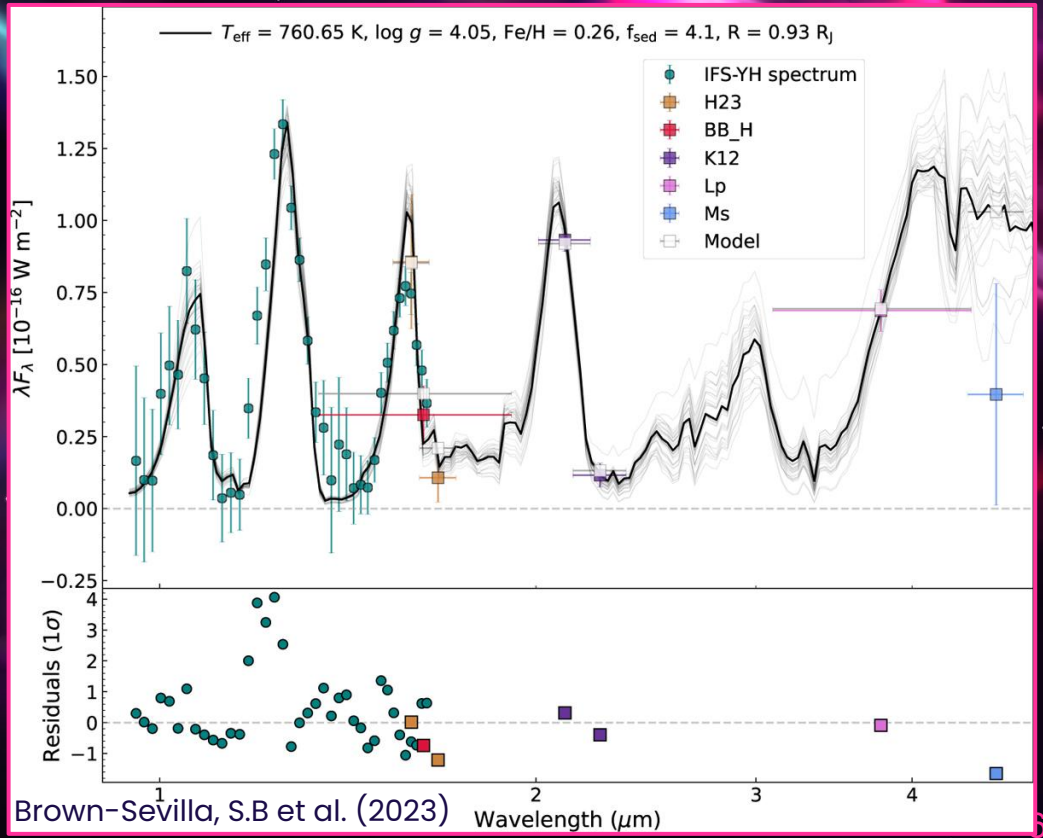
51 Eridani			
Parameter	**Value**	**Method**	**Source**
Angular Diameter [mas]	0.518 ± 0.009	Long baseline interferometry (CHARA/CLASSIC)	Simon & Schaefer (2011)
Stellar Age [Myr]	~18-23	Lithium depletion, isochronal modeling, and FGMK dynamical tracebacks	Various sources
Stellar Mass [$M_\odot$]	1.75 ± 0.05	Isochronal modeling and V-M_K diagrams	Simon & Schaefer (2011)



Simon & Schaefer (2011)

Past Work on the 51 Eridani System

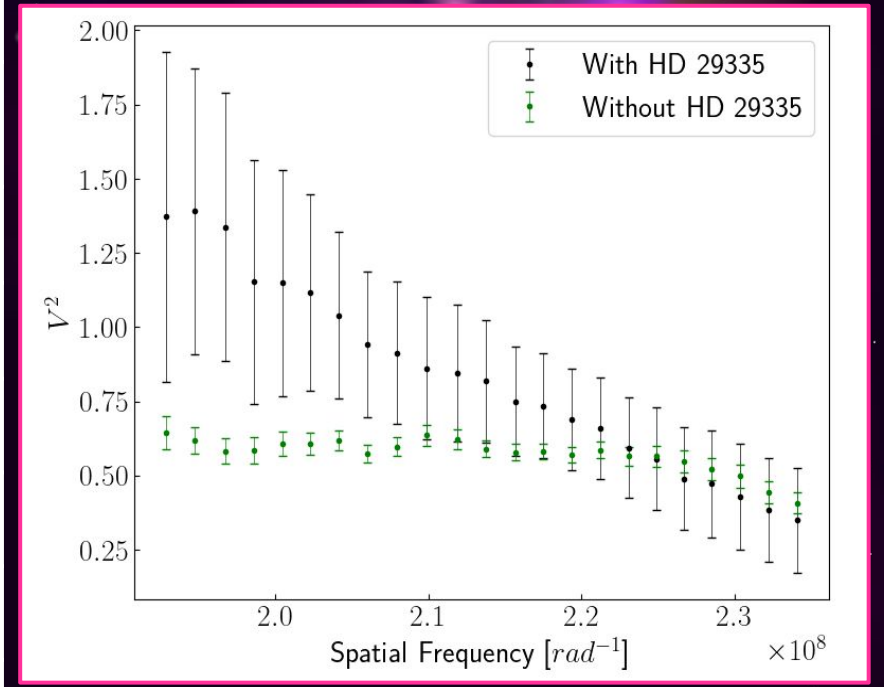
51 Eri b	
Parameter	**Value**
Radius [R_{Jup}]	0.93 ± 0.04
Effective Temperature [K]	807 ± 45
Planetary Mass [M_{Jup}]	3.9 ± 0.4



Brown-Sevilla, S.B et al. (2023)

Observations:

PAVO			
Date (UT)	Baseline	Brackets	Calibrators
2015-10-11	E1/W1	7 (5)	HD 28375 HD 27563 HD 29335*
2015-10-12	S2/E2	9 (7)	HD 28375 HD 27563 HD 29335*
2015-11-06	E2/W1	3 (1)	HD 27563 HD 29335*
2016-11-09	W2/E2	3 (1)	HD 27563 HD 29335*
CLASSIC			
Date (UT)	Baseline	Brackets	Calibrators
2021-08-25	S1/E1	1 (0)	HD 26912*
2021-08-26	S1/E1	1(0)	HD 26912*
2021-08-27	S1/E1	4(3)	HD 29248 HD 28736



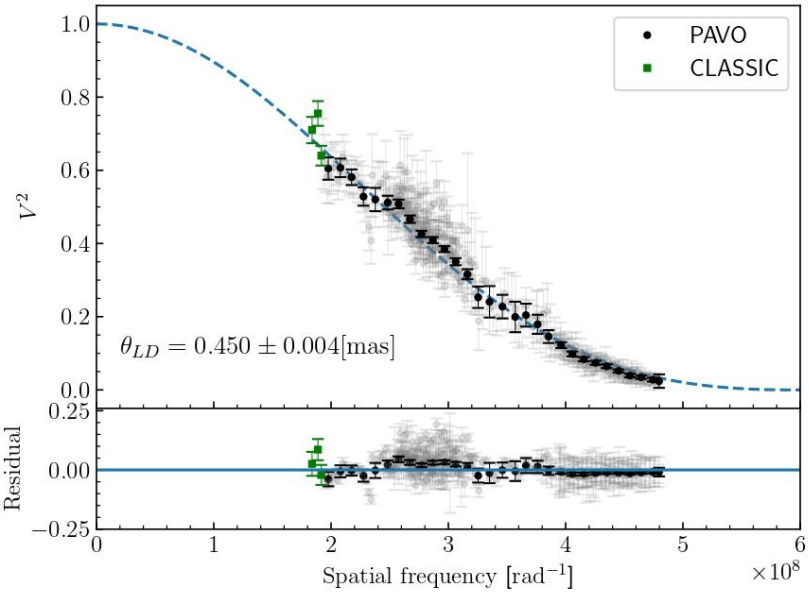
Data Calibration Results:

- ★ Used the bolometric flux and angular diameter to determine a temperature and limb darkened coefficient
- ★ Iterated this process until minimal or no change was seen
- ★ Final results:
  - **θ_{LD} = 0.450 ± 0.004 mas (PAVO)**
  - θ_{LD} = 0.425 ± 0.026 mas (CLASSIC)
  - **T_{eff} = 7424 ± 45 K**
  - **$L_{\star}$ = 5.72 ± 0.1 $L_{\odot}$**
  - **$R_{\star}$ = 1.45 ± 0.01 $R_{\odot}$**

Stefan-Boltzmann equation:

$$L = 4\pi\sigma R^2 T^4$$

Elliott et al. (2024) submitted to arxiv & the PASA



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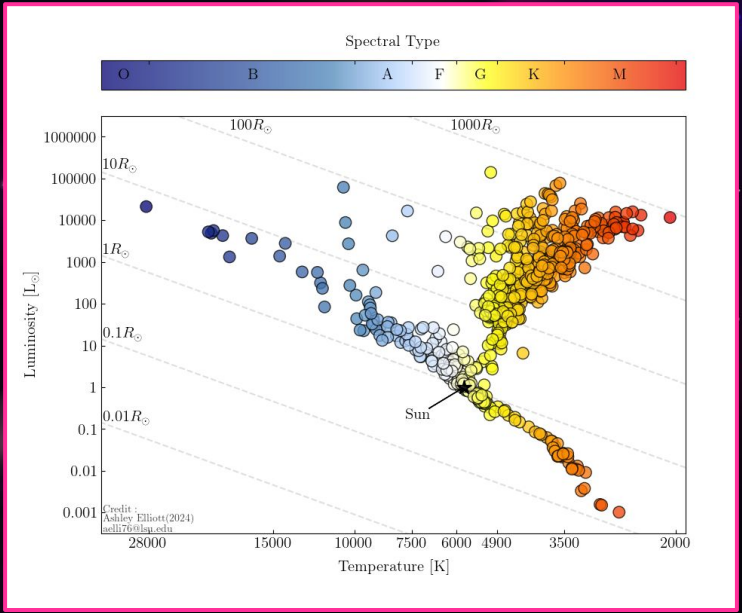


Age and Mass Modeling

- ★ Used two stellar evolution models
  - PAdova and TRieste Stellar Evolution Code (PARSEC)
  - GARching Stellar Evolution Code (GARSTEC)
- ★ 51 Eri is considered to be either pre-main sequence (PMS) or zero-age main sequence (ZAMS)
  -

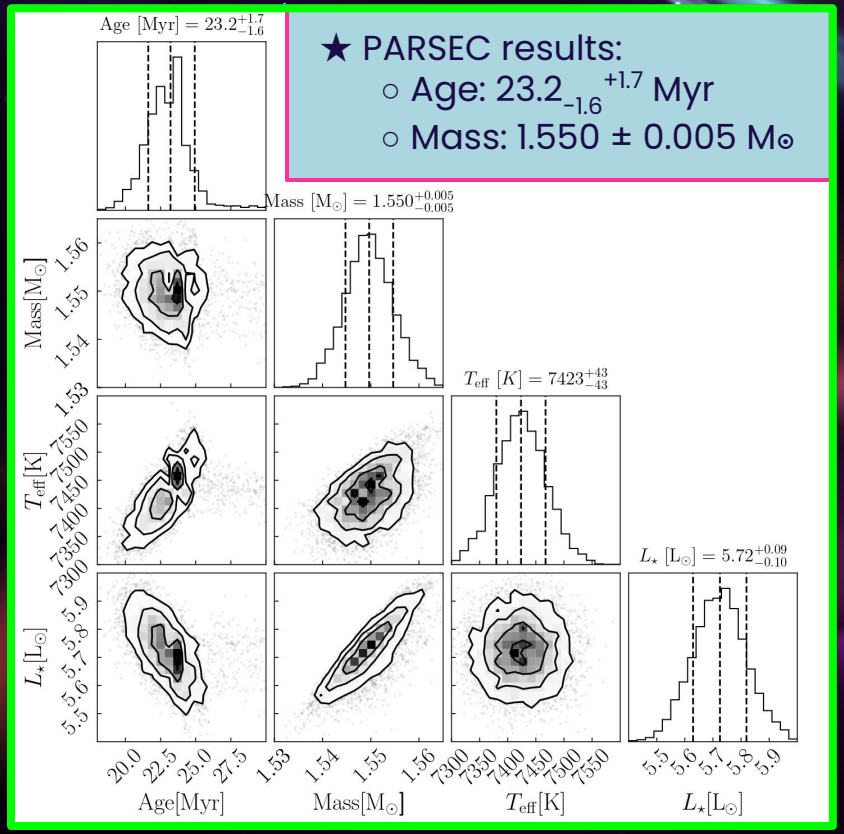
Modeling (cont).:

General Process for both models:

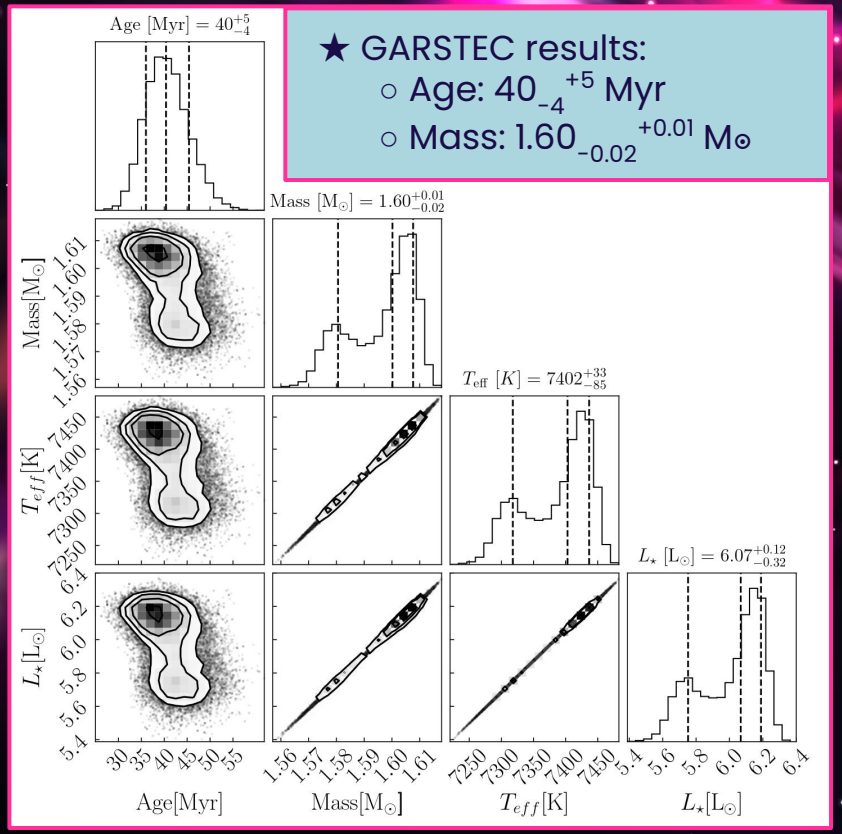
★ PARSEC:
- Output isochrones
- Interpolate in 1-D to get finer grid
- Interpolate again in 2-D to extract an age and mass
- Monte Carlo simulation for errors

★ GARSTEC:
- Ran GARSTEC models through bagemass, providing priors
- Ran Monte Carlo simulation for errors

Results:



★ PARSEC results:
- Age: $23.2_{-1.6}^{+1.7}$ Myr
- Mass: 1.550 ± 0.005 M⊙



★ GARSTEC results:
- Age: 40_{-4}^{+5} Myr
- Mass: $1.60_{-0.02}^{+0.01}$ M⊙

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→

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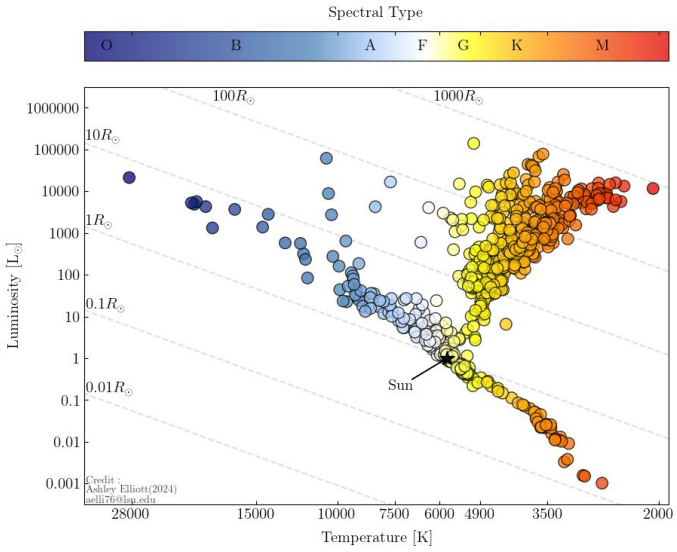
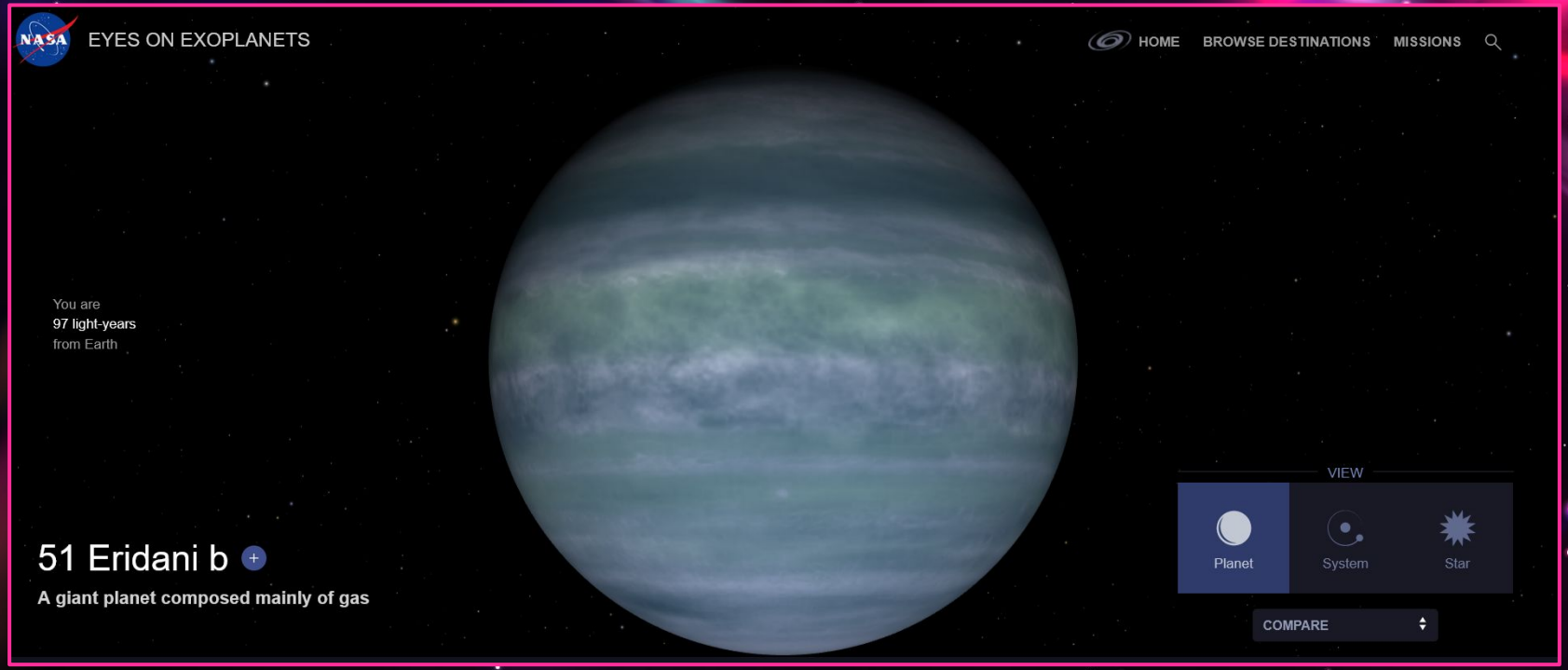
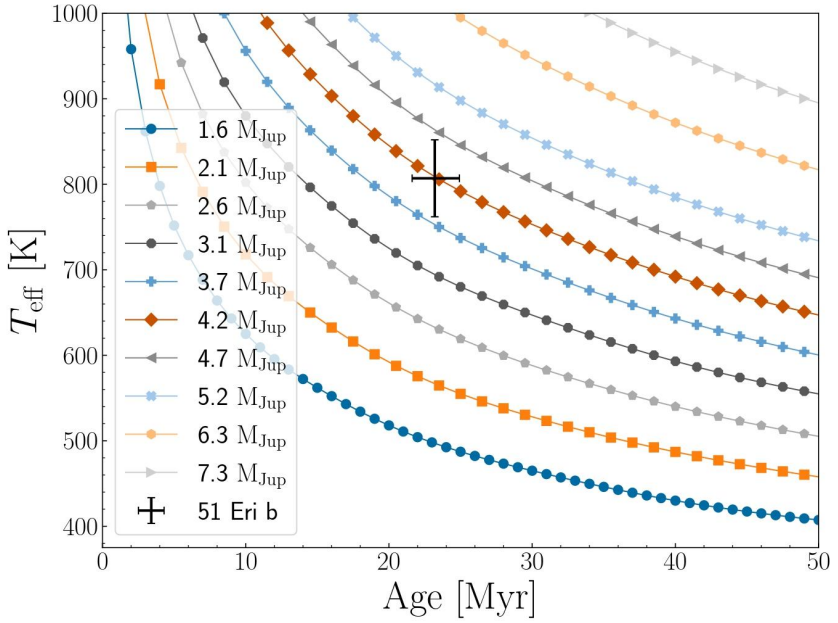


Now onto the planet...

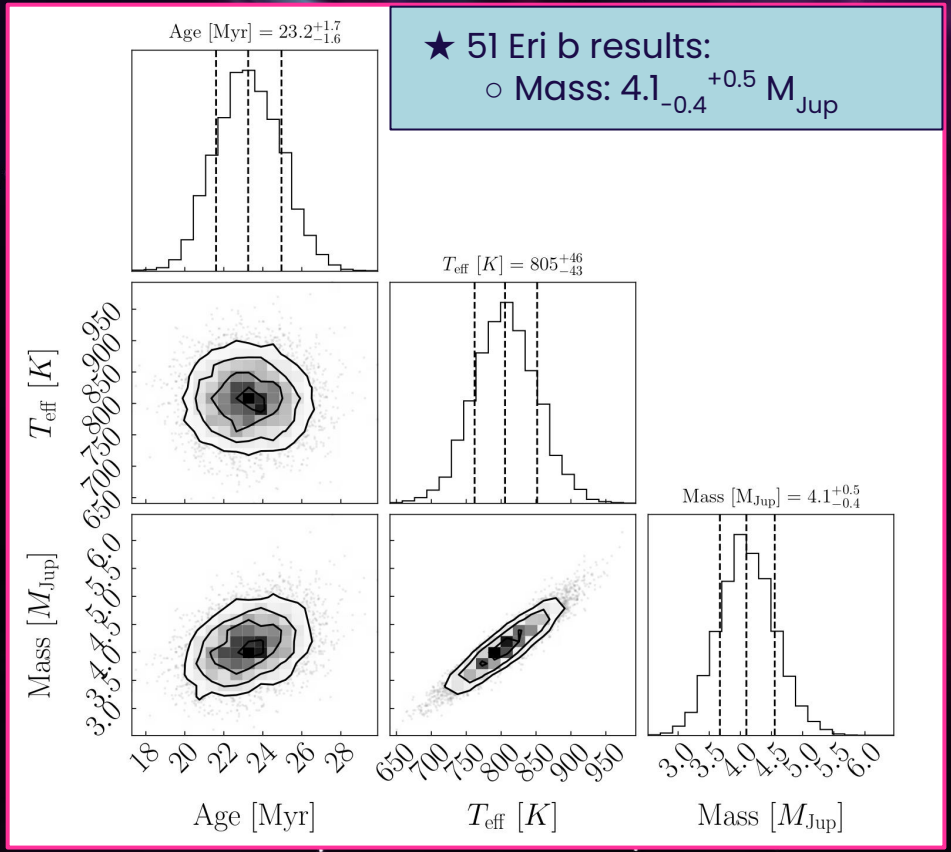


Planet Analysis:

- ★ Age is same as star
- ★ Used Sonora Bobcat models to estimate a mass
  - Designed to study L-, T-, and Y- type brown dwarfs and self-luminous exoplanets



Results:



★ 51 Eri b results:
- Mass: $4.1_{-0.4}^{+0.5}$ M_{Jup}

Discussion:

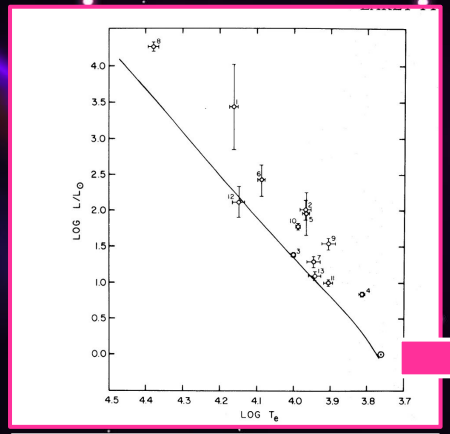
Stellar Parameters:

- ★ Angular diameter is 7σ off from Simon & Schaefer's diameter
- ★ Mass agrees with Simon & Schaefer's mass determined using a V-M_K diagram to estimate a mass
- ★ Age is in good agreement (within 1-2σ) with estimates in the literature

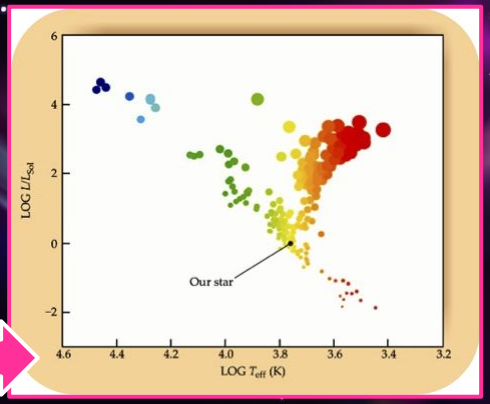
Planetary Parameters:

- ★ Mass is generally in agreement with most estimates in the literature
- ★ Results support ruling out the cold-start formation theory
- ★ Favors either the hot- or warm- start formation theory

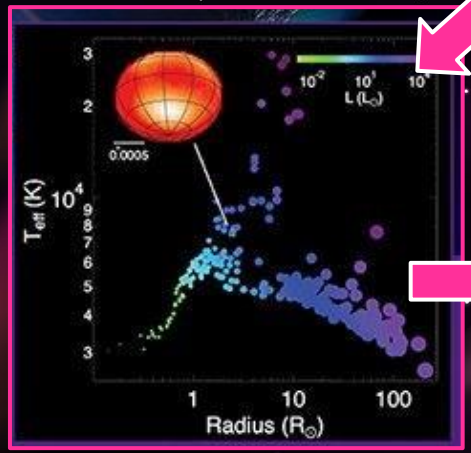
HR Diagram



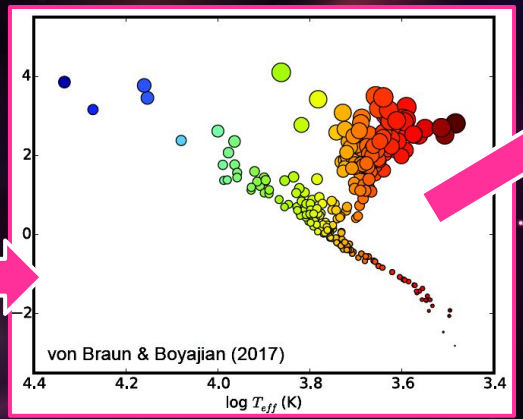
Code et al. 1976



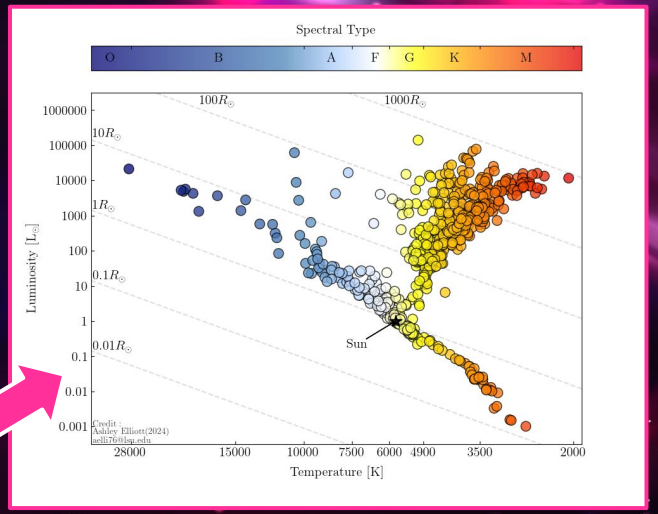
Physics Today (2009)



JAI (2013)

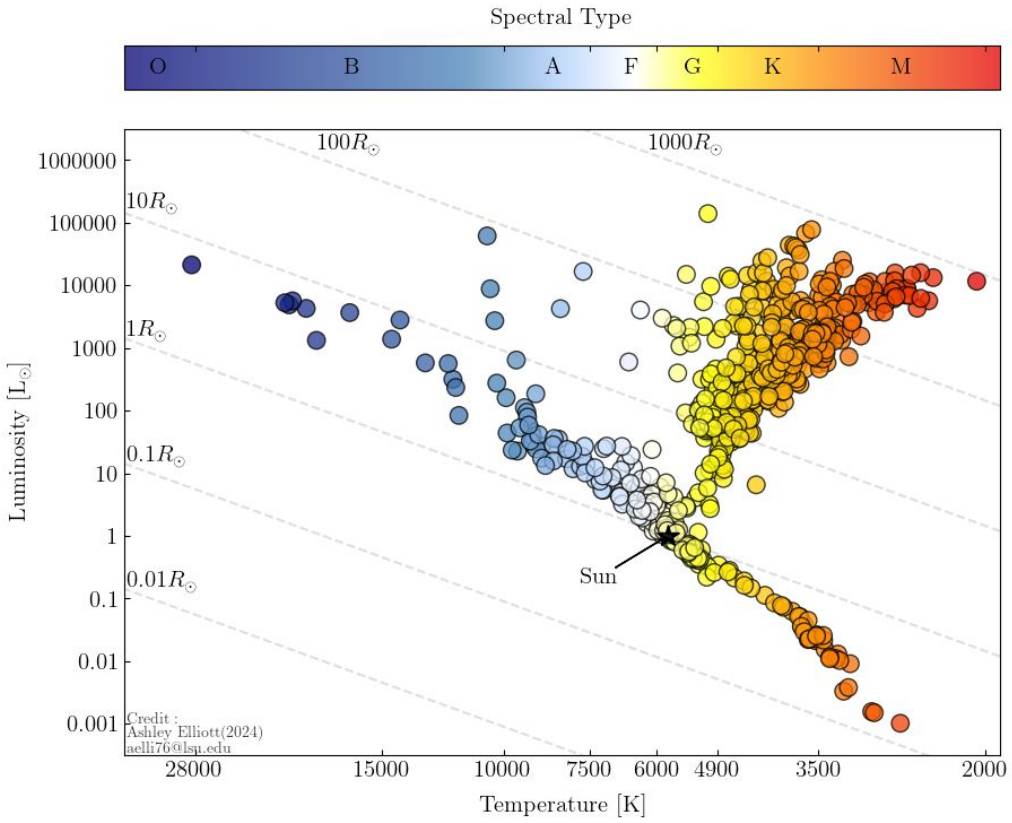


Springer Book (2017)



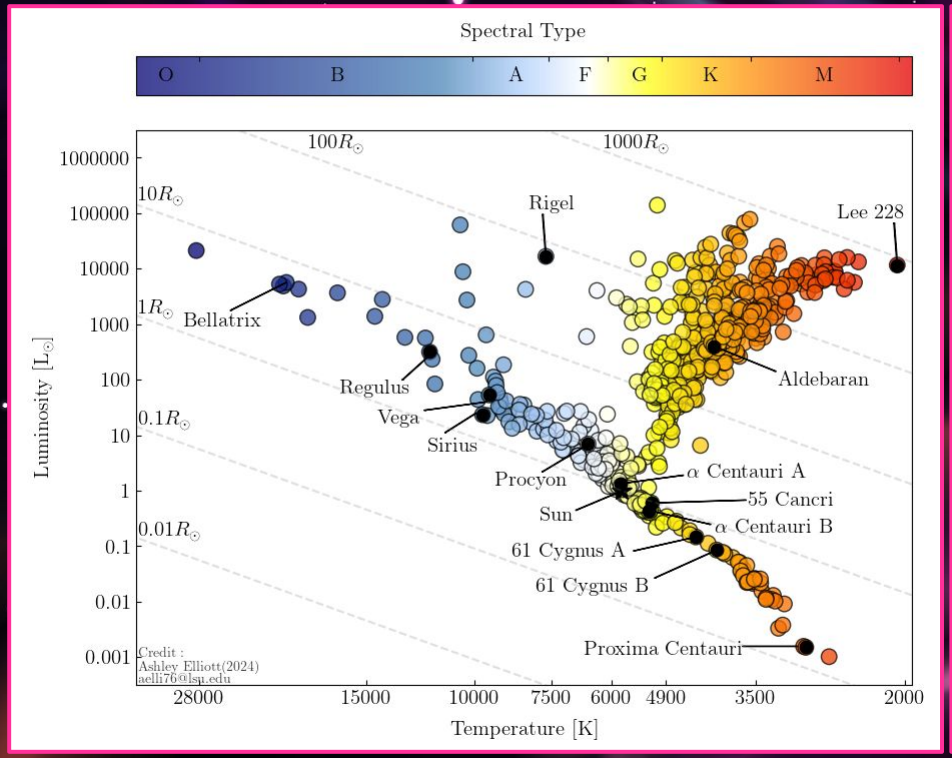
Ashley Elliott (2023)

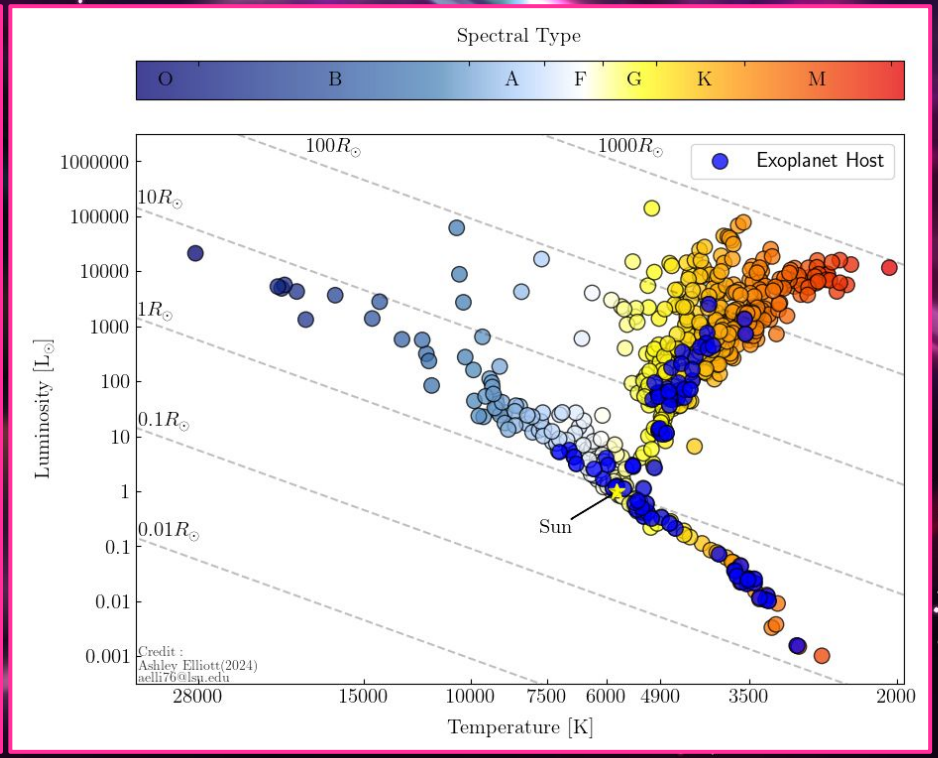
HR Diagram



- ★ 693 unique stars
- ★ Previous diagram by von Braun & Boyajian had ~300 unique sources
- ★ Inspiration to update: a birthday present for Stephen Ridgeway

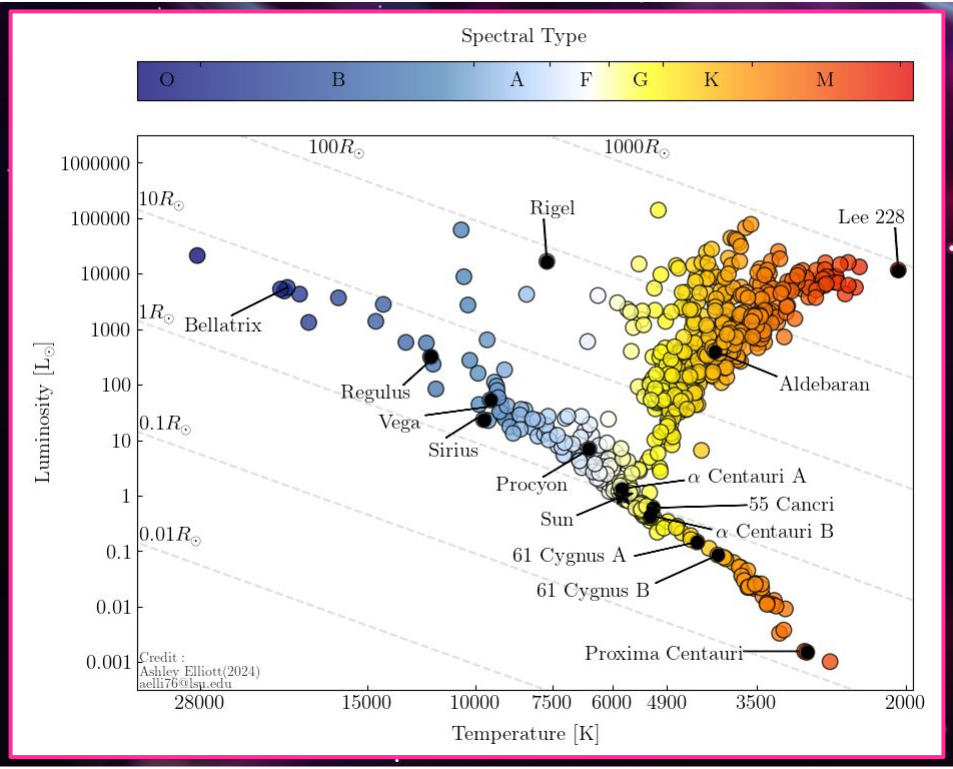
84 exoplanet hosts





http://chara.gsu.edu/science-highlights/stellar-diameters

Thank you! Any questions?



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References

1. Baines E.~K., White R.~J., Huber D., Jones J., Boyajian T., McAlister H.~A., ten Brummelaar T.~A., et al., 2012, ApJ, 761, 57. doi:10.1088/0004-637X/761/1/57
2. Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127. doi:10.1111/j.1365-2966.2012.21948.x
3. Brown-Sevilla, S.~B., Maire, A.-L., Molli{\`e}re, P., et al.\ 2023, \aap, 673, A98. doi:10.1051/0004-6361/202244826
4. Choi J., Dotter A., Conroy C., Cantiello M., Paxton B., Johnson B. D., 2016, ApJ 823 102
5. Dotter A., 2016, ApJS 222 8
6. Dupuy T. J., Brandt G. M., Brandt T. D., 2022, MNRAS, 509,4411
7. Ireland M. J., et al., 2008, in Schöller M., Danchi W. C., Delplancke F., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 7013, Optical and Infrared Interferometry. p. 701324, http://dx.doi.org/10.1117/12.788386
8. Jones J., White R.~J., Quinn S., Ireland M., Boyajian T., Schaefer G., Baines E.~K., 2016, ApJL, 822, L3. doi:10.3847/2041-8205/822/1/L3
9. Macintosh, B., Graham, J.~R., Barman, T., et al.\ 2015, Science, 350, 64. doi:10.1126/science.aac5891
10. Mamajek, E. E. & Bell, C. P. M. 2014, On the age of the β Pictoris moving group. Monthly Notices of the Royal Astronomical Society, 445(3), 2169–2180.
11. Mann A.~W., Feiden G.~A., Gaidos E., Boyajian T., von Braun K., 2015, ApJ, 804, 64. doi:10.1088/0004-637X/804/1/64
12. Maxted P.~F.~L., Serenelli A.~M., Southworth J., 2017, ascl.soft. Ascl:1708.010
13. Miret-Roig, N., Galli, P.~A.~B., Brandner, W., et al.\ 2020, \aap, 642, A179. doi:10.1051/0004-6361/202038765
14. M. Simon and G. H. Schaefer 2011 *ApJ* 743 158
15. Samland M., et al., 2017, A&A,603,A57
16. Spada F., Demarque P., Kim Y.-C., Boyajian T.~S., Brewer J.~M., 2017, ApJ, 838, 161. doi:10.3847/1538-4357/aa661d
17. Spiegel D.~S., Burrows A., 2012, ApJ, 745, 174. doi:10.1088/0004-637X/745/2/174
18. ten Brummelaar T. A., et al., 2005 ApJ 628 453
19. Weiss A., Schlattl H., 2008, Ap\&SS, 316, 99. doi:10.1007/s10509-007-9606-5